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THE ORBIT OF 1972-05B IN ITS FINAL PHASE, WITH GEOPHYSICAL INFERENCES

by

H. Hiller

R O Y A L   A I R C R A F T   E S T A B L I S H M E N T

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SUMMARY

The polar orbit of Heos 2 second-stage rocket, 1972-05B, has been determined on each of the final 16 days before its decay in September 1978, using the RAE orbit refinement program, PROP 6, with about 1360 observations. An accuracy of 30-70 m, both radial and across track, was achieved.

Eleven values of density scale height have been determined from the decrease in perigee height, with a 2 per cent error; seven of these values are within 6 per cent of the *CIRA 1972* reference-atmosphere values, the rms value being 4 per cent higher than *CIRA*.

The rotation rate of the upper atmosphere, Λ , was determined from the decrease in orbital inclination as $\Lambda = 1.40 \pm 0.05$ rev/day; *ie* a strong west-to-east zonal wind of 160 ± 20 m/s, at a mean height of about 240 km. The local time was 01-02 h; solar activity was high; and the latitude of perigee moved steadily from 10°N to 67°S.

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1   INTRODUCTION

The ESRO highly-eccentric-orbit satellite Heos 2 (1972-05A) was launched into an orbit of eccentricity 0.95 on 1972 January 31 by NASA. The second-stage Ablestar rocket, 1972-05B, entered a much lower eccentricity polar orbit (e ≈ 0.06) with a life of about $6\frac{1}{2}$ years and numerous orbits are being determined at the University of Aston; here the orbit is analysed only in the final 16 days of its orbital life, 1978 September 12-27. The North American Air Defense Command (NORAD) kindly supplied about 2500 observations for this 16-day period.

The RAE orbit refinement program[1], in the PROP 6 version (which has a limit of 100 observations per orbit), has been used to determine 16 daily orbits with about 1500 of the NORAD observations, and an additional 70 from the US Navy Navspasur system.

The upper-atmosphere rotation rate has been determined from the decrease in orbital inclination to give the zonal wind speed near 240 km height, and the density scale height has been evaluated over the height band 200-270 km from the decrease in perigee height.

2   THE ORBIT

About 1360 observations were used, with a further 200 or so rejected, in the final determination of the 16 daily orbits for 1978 September 12-27, the last orbit being at an epoch 13 hours before decay. The orbital elements derived are listed in Table 1, with standard deviations.

The sd in inclination, i , varies between 0.0003 and 0.0006°, and in eccentricity, e , from 4×10^{-6} to 7×10^{-6}. These are equivalent to between 30 and 70 m in position for both i and e . This is an excellent accuracy for an orbit so near decay. The sd in right ascension of the node, Ω , is between 0.0002 and 0.0008°; for argument of perigee, ω , or mean anomaly at epoch, M_0 , the sd varies from 0.03 to 0.19°. Figs 1 to 5 show the variations of i, a, e, Ω and ω . Although the overall drop in inclination over the 16 days was only 0.02° (see Fig 1), it was sufficient to determine accurately the upper-atmosphere wind (section 5).

3   VARIATION IN PERIGEE HEIGHT

Perigee height is required for determining density scale height and the heights applicable to density scale height and atmospheric rotation. Values of semi major axis, a , and eccentricity, e , from Table 1 are used to calculate perigee height over a spherical Earth, h_p , where

$$h_p = a(1 - e) - R , \tag{1}$$

where R , the Earth's mean equatorial radius, is taken to be 6378.14 km. Next, the perturbation Δe , in e , due to zonal harmonic and lunisolar effects, is obtained using the PROD computer program[2] and cleared from h_p to give Q where

$$Q = h_p + a\Delta e , \tag{2}$$

Table 1

Orbital parameters for Heos 2 second-stage rocket, with standard deviations

Orbit	Date 1978 Sep	MJD	a	e	i	Ω	ω	M_0	M_1	M_2	M_3	M_4	ε	D	N
1	12	43763.0	6659.3724 11	0.007233 6	89.7371 5	18.6781 5	9.66 3	90.66 3	5753.312 1	2.058 6			0.39	0.9	95
2	13	64.0	6656.0261 10	0.006900 4	89.7366 4	18.6376 4	5.62 3	85.85 3	5757.654 1	2.228 4			0.32	0.9	87
3	14	65.0	6652.6892 9	0.006591 5	89.7360 5	18.5984 4	1.42 3	85.61 3	5761.989 1	2.091 5			0.32	0.9	81
4	15	66.0	6649.4293 10	0.006280 5	89.7348 5	18.5580 4	357.25 4	89.59 4	5766.228 1	2.070 5			0.33	0.9	75
5	16	67.0	6646.1362 8	0.005979 5	89.7341 4	18.5179 4	352.96 3	97.92 3	5770.517 1	2.224 4			0.28	0.9	72
6	17	68.0	6642.5396 37	0.005662 4	89.7337 4	18.4784 4	348.06 4	111.34 4	5775.206 5	2.408 11			0.21	0.6	76
7	18	69.0	6638.7040 13	0.005378 7	89.7338 5	18.4373 7	343.50 5	129.25 4	5780.215 2	2.556 4			0.32	1.0	91
8	19	70.0	6634.7378 8	0.005098 4	89.7325 3	18.3974 4	338.57 3	152.64 3	5785.401 1	2.643 3			0.29	0.9	92
9	20	71.0	6630.4886 11	0.004780 5	89.7332 4	18.3562 2	333.63 4	181.37 3	5790.966 1	2.876 5			0.29	0.9	80
10	21	72.0	6625.8551 23	0.004516 5	89.7319 4	18.3144 4	328.52 5	216.07 5	5797.045 3	3.285 5	0.27 2		0.29	0.9	90
11	22	73.0	6620.2125 9	0.004197 6	89.7289 5	18.2716 6	323.53 7	257.33 7	5804.462 1	3.934 5			0.36	0.9	83
12	23	74.0	6613.4266 14	0.003885 5	89.7276 5	18.2317 5	317.63 6	307.52 6	5813.402 2	5.058 8			0.30	0.8	71
13	24	75.0	6604.9725 26	0.003537 5	89.7261 4	18.1873 4	311.83 9	7.70 9	5824.573 3	6.129 5	0.20 2		0.38	0.9	96
14	25	76.0	6594.8032 20	0.003114 4	89.7245 4	18.1460 3	306.15 11	79.99 11	5838.057 3	7.763 7	0.75 2		0.35	0.9	92
15	26	77.0	6579.6208 40	0.002604 7	89.7227 6	18.1006 8	300.54 16	168.44 16	5858.286 5	12.24 2	1.73 3	2.3 1	0.43	0.9	69
16	27	78.0	6551.8756 67	0.001815 6	89.7175 5	18.0595 4	292.69 19	285.98 19	5895.556 9	30.25 3	16.8 2	16.5* 2	0.48	0.9	94

* M_5 = 11.2 ± 0.8

Key: MJD   Modified Julian Day
       a   semi major axis (km)
       e   eccentricity
       i   inclination (deg)
       Ω   right ascension of node (deg)
       ω   argument of perigee (deg)

M_0 mean anomaly at epoch (deg)
M_1 mean motion, n (deg/day)
M_2–M_5 additional coefficients in polynomial for M
ε   measure of fit
D   time coverage of observations (days)
N   number of observations used

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which should be free of gravitational perturbations. These values of Q are plotted in Fig 6, and its decrease ΔQ is used in the determination of scale height (section 4).

Perigee height, y_p , over an oblate Earth is obtained by allowing for (a) the variation in local Earth radius at perigee latitude and (b) the dynamical effects of the Earth's oblateness[3], to give

$$y_p = h_p + 21.38 \sin^2\omega + (1.67 - 3.32 \sin^2\omega) \quad ,$$

for 1972-05B at inclination 90°. Hence

$$y_p = h_p + 18.06 \sin^2\omega + 1.67 \qquad \text{km} \qquad (3)$$

and is also plotted in Fig 6.

4 DENSITY SCALE HEIGHT

The decrease in Q , shown in Fig 6 to be very well defined, depends on the density scale height H , and analysis of the variation in Q should therefore yield reliable values of H .

Low-eccentricity theory is needed because z $(= ae/H)$ is less than 3, and, for an orbit in an oblate atmosphere, we have[4]

$$\frac{da}{dx} = y_0 + \tfrac{1}{2}e\left(4 - 3y_0^2 - y_0 y_2\right) - \tfrac{1}{2}c \cos 2\omega(y_0 - 2y_2 + y_0 y_3) \quad , \qquad (4)$$

where $x = ae$, $y_r = I_r/I_1$, I_r being the Bessel function of the first kind and imaginary argument, of order r and argument z ; and $c = \epsilon'a(1 - e) \sin^2 i/2H$, with ϵ' , the ellipticity of the atmosphere, taken equal to the Earth's ellipticity, 0.00335.

In previous orbital analyses using low-eccentricity theory, the perigee height has been below 200 km and equation (4) has been used as it stands. Here, however, values of H are being determined at heights up to about 260 km, where the day-to-night variation in air density is large enough to affect equation (4) appreciably. In an atmosphere with maximum daytime density ρ_{max} (at 14 h local time) and minimum night-time density ρ_{min} (at 02 h local time), the equation for da/dx for a low-eccentricity orbit is[5]

$$\frac{da}{dx} = \frac{y_0 + F \cos \phi_p}{1 + \tfrac{1}{2}F \cos \phi_p (y_0 + y_2)} \{1 + 0(e)\} \quad , \qquad (5)$$

where ϕ_p is the angular distance of perigee from the centre of the diurnal bulge, $F = (f - 1)/(f + 1)$ and $f = \rho_{max}/\rho_{min}$. In the conditions experienced by 1972-05B (exospheric temperature at night $\simeq$ 900 K), the COSPAR International Reference Atmosphere 1972 (Ref 6) gives $f = 1.3$ at 200 km increasing to $f = 1.7$ at 260 km height, so that $0.15 < F < 0.25$. Also $z \simeq 1$, so that $\tfrac{1}{2}(y_0 + y_2) = 1$. Assuming that equation (5) can be expanded in powers of F , we find

$$\frac{da}{dx} = y_0 - \tfrac{1}{2}F \cos \phi_p\left(y_0^2 + y_0 y_2 - 2\right) + 0(F^2, e) \quad . \tag{6}$$

If we assume that the effects of c and F are simply additive, the equation for da/dx in an oblate atmosphere with day-to-night variation in density may, from (4) and (6), be written

$$\frac{da}{dx} = y_0 + \tfrac{1}{2}e\left(4 - 3y_0^2 - y_0 y_2\right) - \tfrac{1}{2}c \cos 2\omega(y_0 - 2y_2 + y_0 y_3)$$

$$- \tfrac{1}{2}F \cos \phi_p\left(y_0^2 + y_0 y_2 - 2\right) + 0(c^2, F^2, e^2, \text{etc}) \quad . \tag{7}$$

For 1972-05B the local time at perigee is near 02 h, diametrically opposite the centre of the diurnal bulge when $\omega = 0$, so that, by a convenient chance, $\phi_p = |180^{\circ} - \omega|$. Thus, for 1972-05B in its final days, equation (7) becomes

$$\frac{da}{dx} = y_0 + \tfrac{1}{2}e\left(4 - 3y_0^2 - y_0 y_2\right) - \tfrac{1}{2}c \cos 2\omega(y_0 - 2y_2 + y_0 y_3)$$

$$+ \tfrac{1}{2}F \cos \omega\left(y_0^2 + y_0 y_2 - 2\right) = \beta \ , \quad \text{say} \quad . \tag{8}$$

This theoretical value of da/dx must be matched with the observational value which, following Ref 7, is given by

$$\frac{da}{dx} = 1 \left/ \left(1 + \frac{3\Delta Q}{4a} \cdot \frac{M_{1A} + M_{1B}}{M_{1B} - M_{1A}}\right) \right. = \alpha \ , \quad \text{say} \ , \tag{9}$$

where ΔQ is the change in Q over a time interval Δt , selected to ensure that $|\Delta Q| \geqslant 3$ km , and M_{1A} and M_{1B} are the initial and final values of the mean motion M_1 during the time interval Δt . In (8) and (9) the values of a, e, cos 2ω and cos ω are taken as the mean during this time interval.

The density scale height H can now be determined by guessing two values of H , say H_1 and H_2 , which give β_1 and β_2 from equation (8), and then by interpolation using

$$H = \frac{H_1(\beta_2 - \alpha) + H_2(\alpha - \beta_1)}{\beta_2 - \beta_1} \quad . \tag{10}$$

These observational values of H are plotted in Fig 7 as circles with vertical rms error bars (calculated to be near 1 km for all values of H) and horizontal bars representing the time intervals over which the values of H are calculated.

Values of H have also been calculated using the *CIRA 1972* reference atmosphere[6], for the appropriate heights and exospheric temperatures, T_∞ , and are plotted in Fig 7 as crosses. The values of T_∞ are calculated using appropriate values of solar 10.7 cm

radiation energy (plotted in Fig 7) and geomagnetic index, with allowance for semi-annual effects[8]. Care must be taken here to ensure that local time used to calculate T_∞ is not that at perigee but averaged over a wide arc of the orbit, as discussed in Ref 7. Using local time at perigee would result in errors of up to 100 K in T_∞. Also plotted in Fig 7 is the height y (= $y_p + \gamma H_p$) at which H applies. Values of γ, obtained from Ref 9, vary between 0.4 and 0.8.

Of the eleven observational values of H calculated, with a 2 per cent error, seven are within 6 per cent of the *CIRA 1972* values, the rms value being 4 per cent higher than *CIRA*. This agrees with a previously[10] determined value of 7 per cent higher, also for high solar activity. The four remaining values are 10-15 per cent higher than *CIRA* and Fig 7 shows this occurs during a period of high solar radiation energy. A medium magnetic storm occurred during the final 3 days in orbit (1978 September 25-27), where **Ap** increased from 36 to 51, but this does not seem to have made any significant difference.

The observational values of density scale height, H, plotted in Fig 7 are replotted in Fig 8 against height y, as crosses against a background of density scale height curves, for various T_∞, obtained from *CIRA 1972*. Adjacent to each cross is the value of T_∞, in brackets, which was used to calculate the *CIRA* value of H.

Both atmospheric oblateness ε' and the day-to-night variation in density, measured by F, strongly influence the values of H obtained. If c is taken as zero in equation (8), *ie* for zero ε', the value of H obtained is reduced by 20 per cent in the first few days, is unchanged on September 23-24 (when $\cos 2\omega = 0$), and is increased by 20 per cent on the day of decay. If F is taken as zero in equation (8), H increases by 30 per cent except for the final 4 days (to decay) when the increase is about 20 per cent. There is no reason to suspect that the values of ε' or F used are appreciably in error: but if they were in error by 10 per cent, say, errors of up to $2\frac{1}{2}$ per cent in H would occur.

5   UPPER-ATMOSPHERE ZONAL WIND

5.1   Results

The 16 daily values of inclination determined are listed in Table 1 and plotted in Fig 1. The values were then cleared of lunisolar and geopotential perturbations using the PROD program[2], with numerical integration at 1-day intervals. The modified values are plotted in Fig 9, with standard deviations. The overall decrease in inclination is about 0.023°, about 50 times the mean sd of the values.

Since the orbital inclination is near 90°, the meridional wind has no effect and so the variation in inclination is due to the zonal wind.

The theoretical change in inclination has been calculated for several values of atmospheric rotation rate (expressed as Λ times the Earth's rotation rate) using the RAE computer program ROTATM (for an oblate atmosphere), with daily integration steps. The best fit to the modified inclination values is given by $\Lambda = 1.40 \pm 0.05$ rev/day and is shown in Fig 9, where most of the points are within 2 sd of the curve. This corresponds to a zonal west-to-east wind of 160 ± 20 m/s. Since zonal wind speed depends on local

time, this is plotted along the top of Fig 9; it shows little variation, always being between 01 and 02 h. The orbits are determined for 1978 September, ie equinox and high solar activity conditions; and the latitude of perigee steadily changes from 10°N to 67°S. So, although the effect of aerodynamic forces is spread over a wide arc around perigee, there is a bias towards equatorial rather than polar regions.

The wind speed is also an average over a range of heights, but the mean height y_Λ is given by

$$y_\Lambda = y_p + \lambda H_p$$

where $\lambda = 0.5$, from Ref 11. The mean perigee height y_p is estimated to be near 220 km from Fig 6, while the mean perigee scale height H_p is estimated to be near 40 km. Hence $y_\Lambda \simeq 240$ km .

5.2 Discussion

The analysis of numerous orbits by King-Hele and Walker[12] has indicated that zonal winds at heights of 200-400 km are usually from west to east at local times from 18 to 24 h, and east to west from 04 to 12 h local time. So the west-to-east wind of 160 m/s at 240 km height at 01-02 h local time obtained here is unexpectedly strong. However, it is not so anomalous as appears at first sight, for three reasons.

(1)   The zonal winds are more strongly from west to east near the equator than at higher latitudes (see Fig 14 of Ref 12), and the perigee of 1972-05B travelled from latitude 10°N to latitude near 60°S, so that the effective average latitude was probably about 20°.

(2)   The variation of wind speed with local time depends on latitude, and the maximum west-to-east wind probably occurs at a later local time near the equator. For example, the airglow measurements of Sipler and Biondi[13], for 20 August 1977 at latitude 9°N, indicate a west-to-east wind exceeding 100 m/s between 21 and 02 h, with a value of 125 m/s at 01 h.

(3)   The variation with local time may also depend on solar activity, with the maximum west-to-east wind being somewhat later when solar activity is high. For example, in 1970, when solar activity was high, Roble, Salah and Emery[14] found that, at 240 km height at latitude 42°N, zonal winds were west to east with velocity exceeding 100 m/s from 18 to 01 h on 23-24 February and from 19 to 01 h on 18-19 May. But in 1974, when solar activity was low, Hernandez and Roble[15] found west-to-east winds exceeding 100 m/s from 19 to 23 h at 240 km on 15 August.

The high value of Λ obtained here, 1.40 ± 0.05 rev/day, is paralleled by results from three other satellites, 1969-20B, 1969-94B and 1970-43B, which all give $\Lambda = 1.3 \pm 0.1$ for heights near 240 km at times of high solar activity, for local times of 18-03 h (see Ref 12).

The zonal wind speed in the thermosphere probably varies with height, season, latitude, solar activity, local time and day of the year, as well as being correlated with geomagnetic disturbances and events in the lower atmosphere. The value from 1972-05B, being so well defined, should help in unravelling this complex pattern.

6   CONCLUSIONS

The near-polar orbit of Heos 2 second-stage rocket, 1972-05B, has been determined
daily for the last 16 days in orbit, including an orbit for the day of decay
1978 September 27. About 1360 observations were used, most of which were kindly supplied
by the North American Air Defense Command, NORAD.

For the 16 orbits obtained, given in Table 1, the sd in inclination varies between
0.0003 and 0.0006^{o}, while the sd in eccentricity varies from 4×10^{-6} to 7×10^{-6}; these
variations are both equivalent to 30-70 m in position.

Values of density scale height have been determined from the decrease in perigee
height and compared with the *CIRA 1972* reference atmosphere; the values obtained are
probably accurate to about 2 per cent and are about 4 per cent above *CIRA*, on average.

A value for the atmospheric rotation rate Λ was determined from the decrease in
orbital inclination and found to be $\Lambda = 1.40 \pm 0.05$ rev/day , equivalent to a strong
west-to-east zonal wind of 160 ± 20 m/s at a mean height of about 240 km. The conditions
prevailing were: local time 01-02 h; equinox; high solar activity; and latitude of
perigee between 10°N and 67°S.

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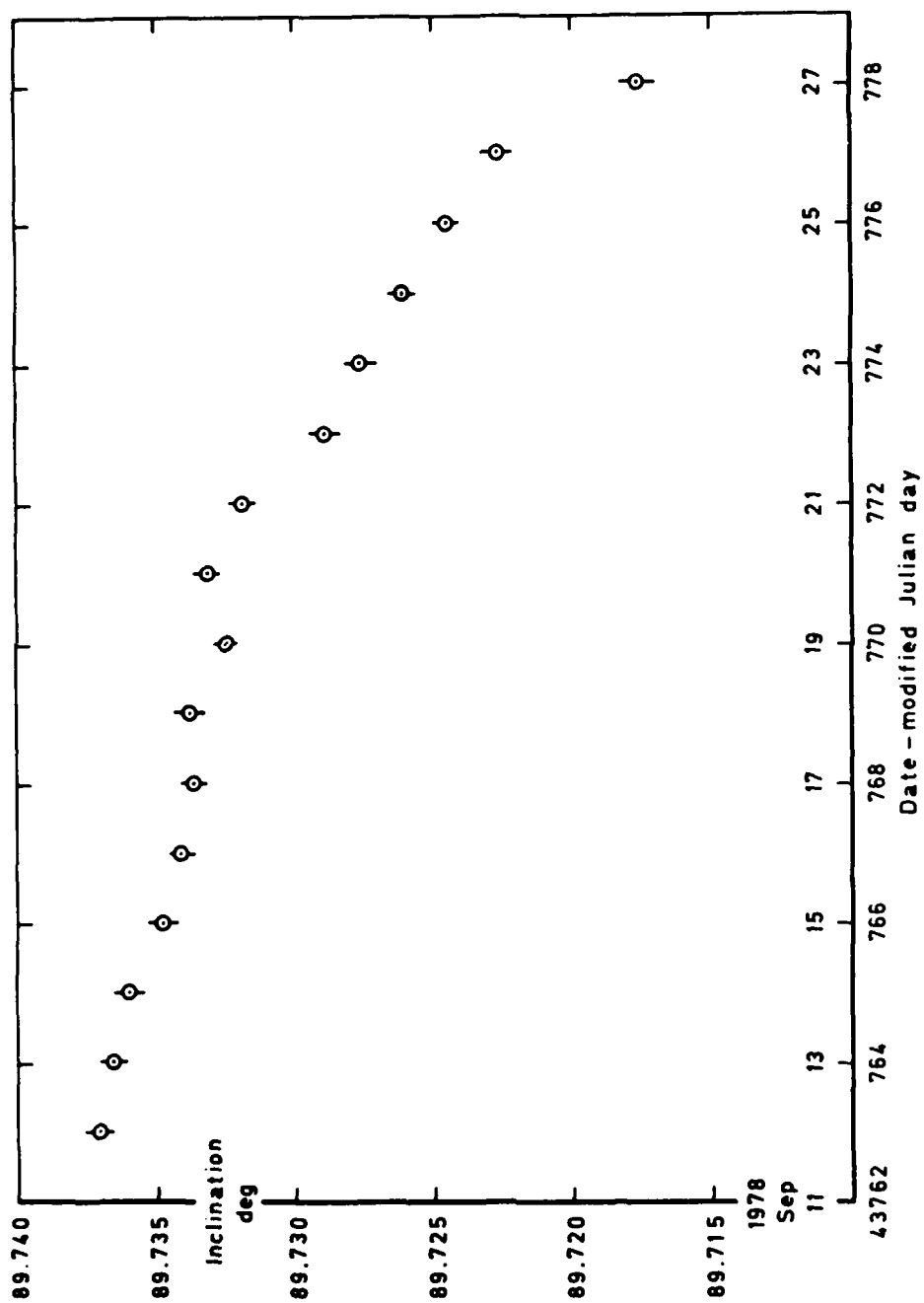| No.	Author	Title, etc
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Fig 1

Fig 1 Observational values of inclination, with sd

Fig 2
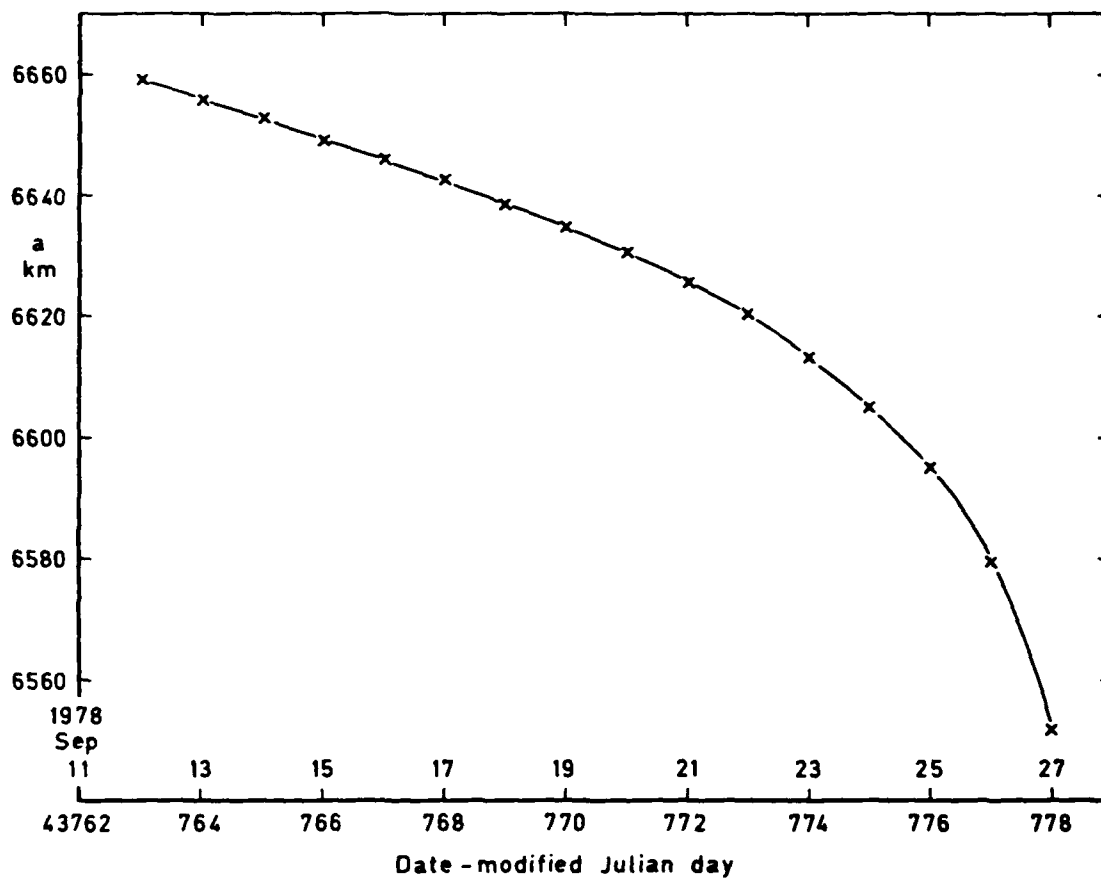
Fig 2   Observational values of semi major axis, a
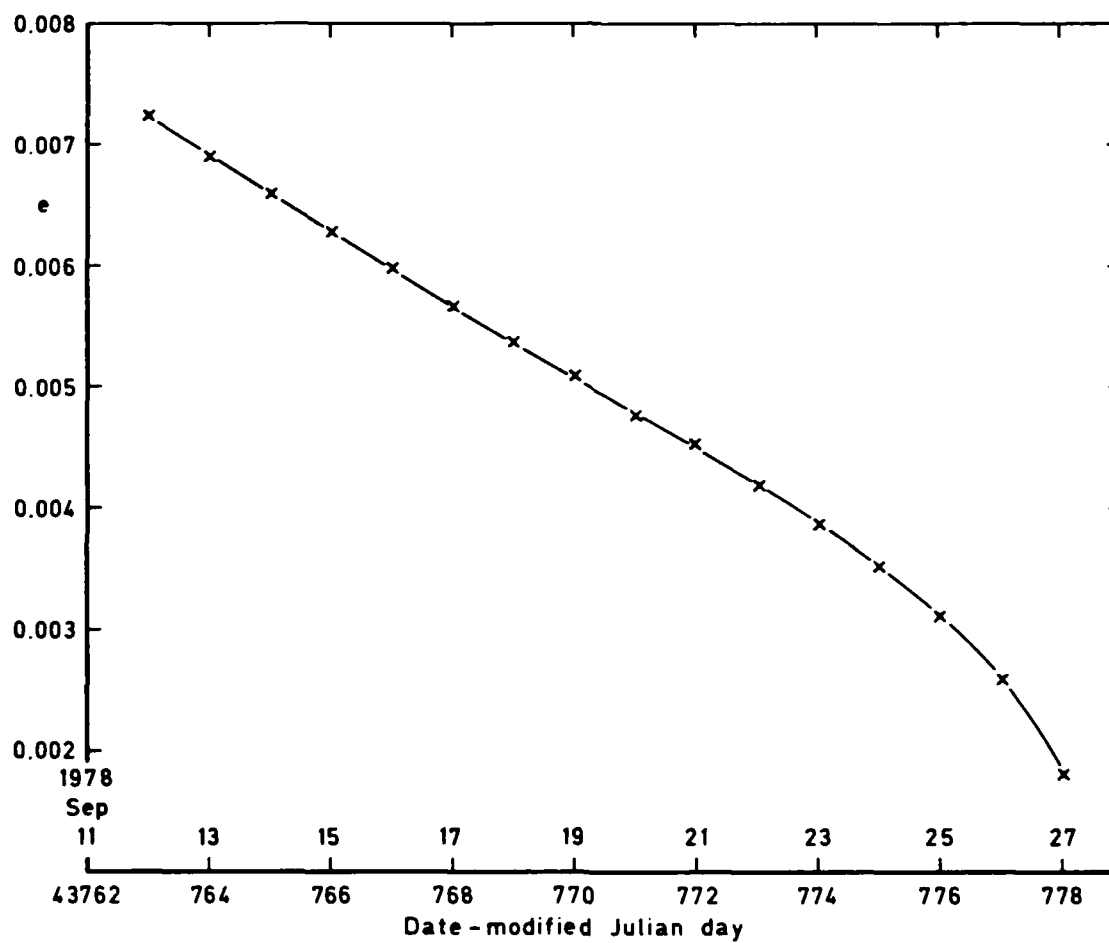
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Fig 3

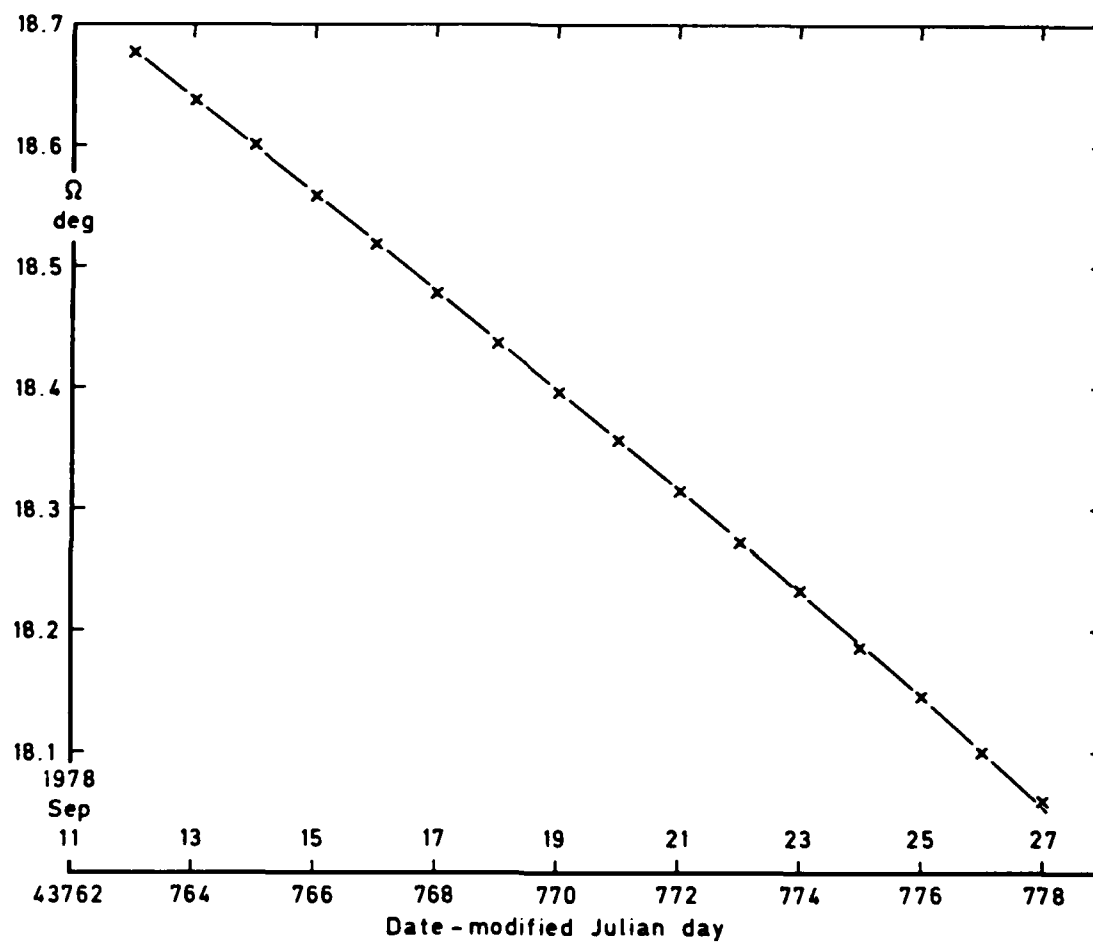Fig 3   Observational values of eccentricity, e

Fig 4

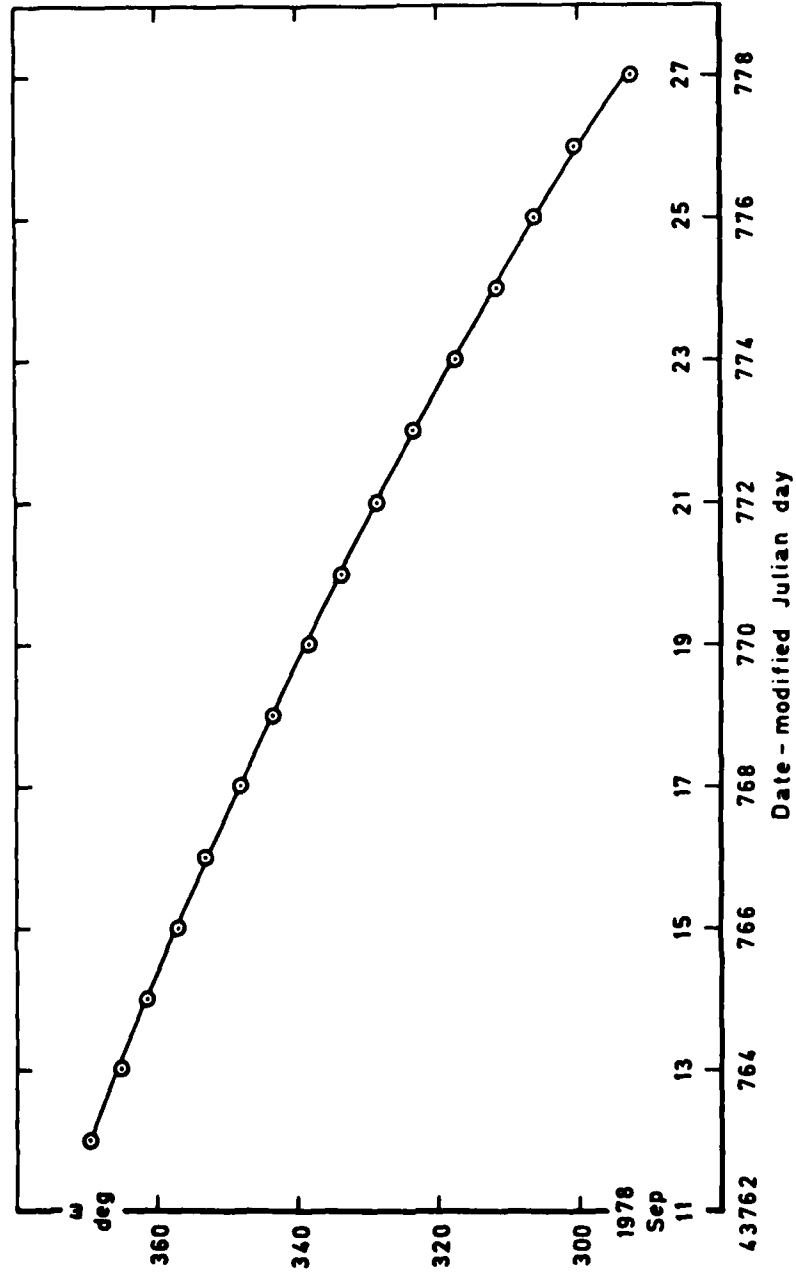Fig 4   Observational values of right ascension of the node, Ω

Fig 5

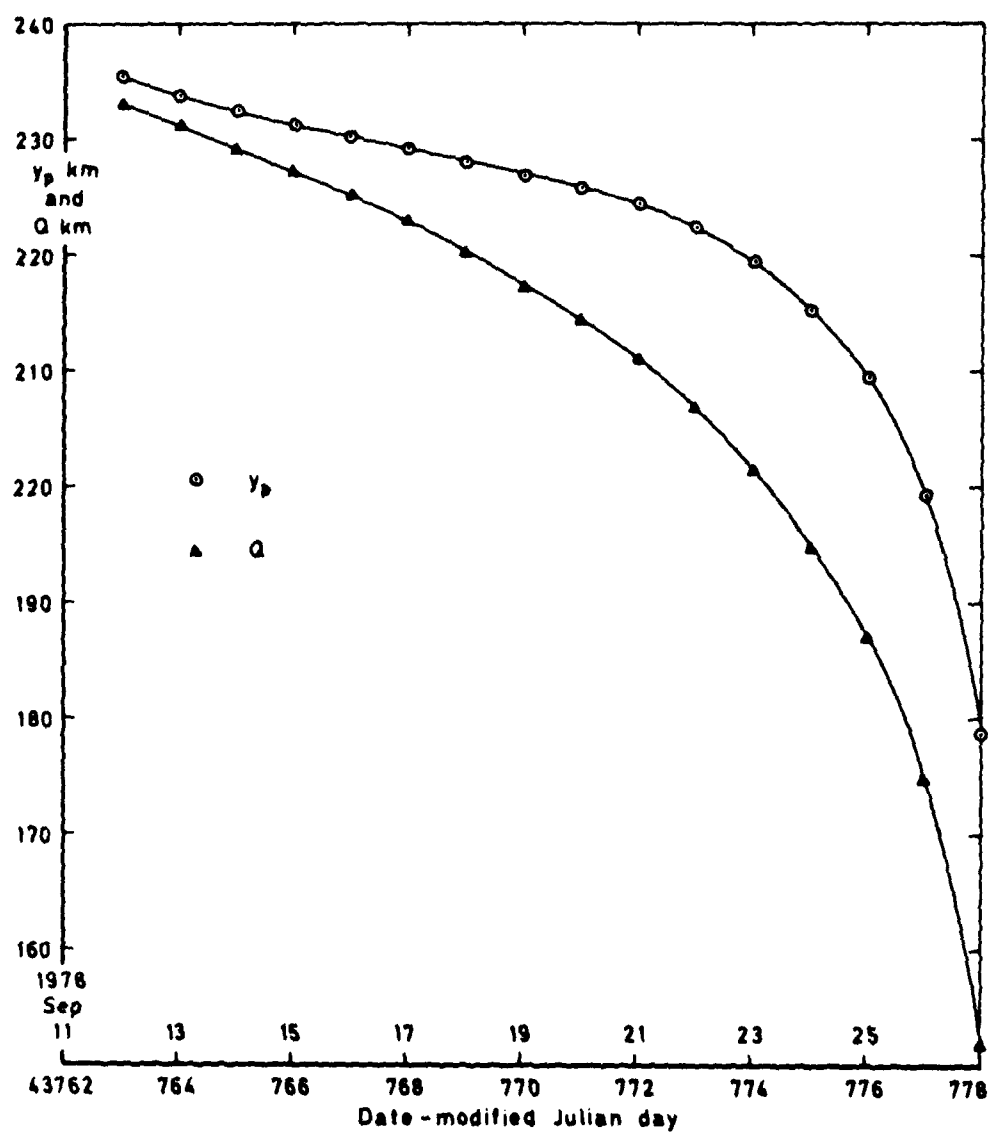Fig 5   Observational values of argument of perigee, ω

Fig 6

Fig 6   Perigee heights: y_p over an oblate Earth; and Q over a spherical Earth, cleared of gravitational perturbations
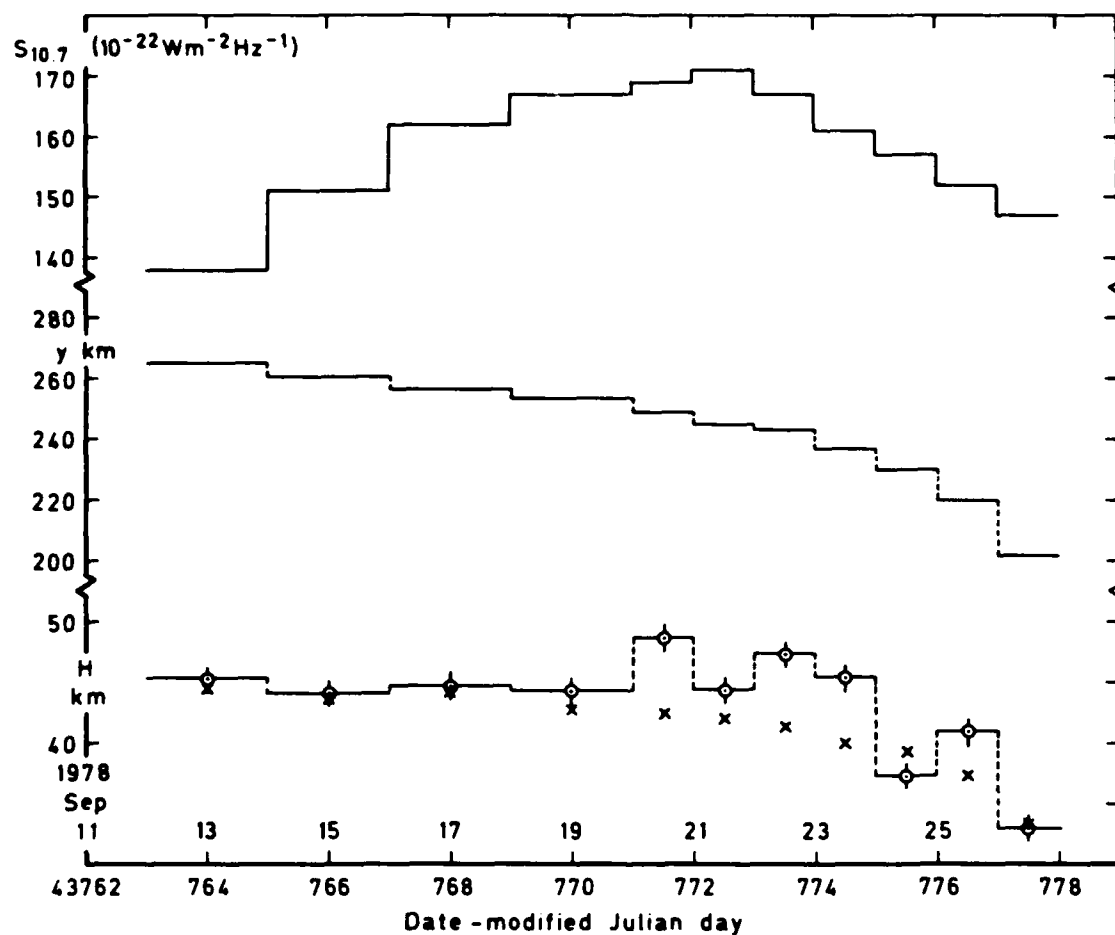
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Fig 7

Fig 7   Density scale height H , its height of application y , and solar radiation energy $S_{10.7}$
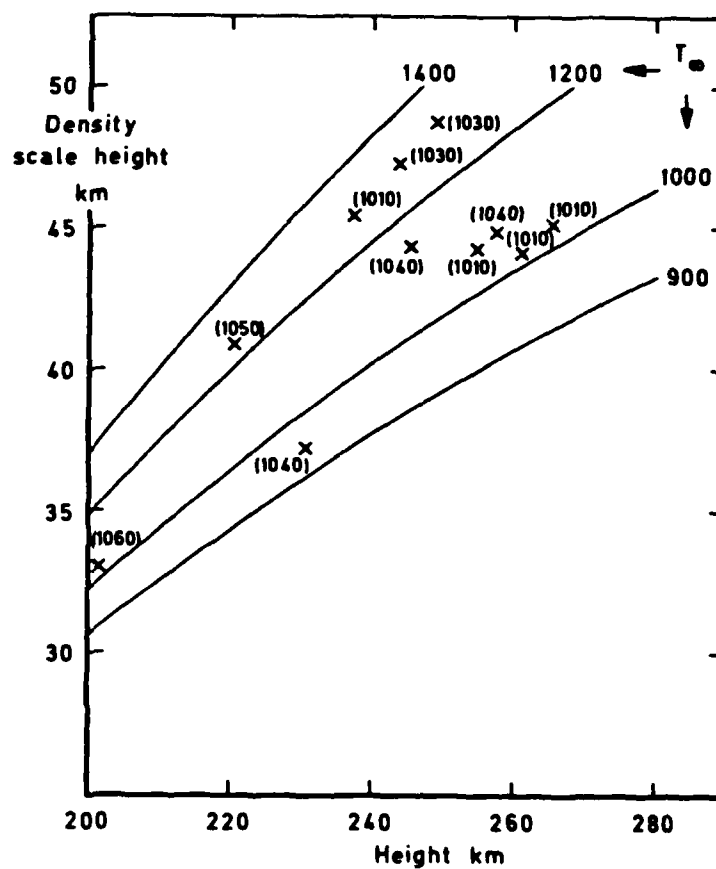
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Fig 8

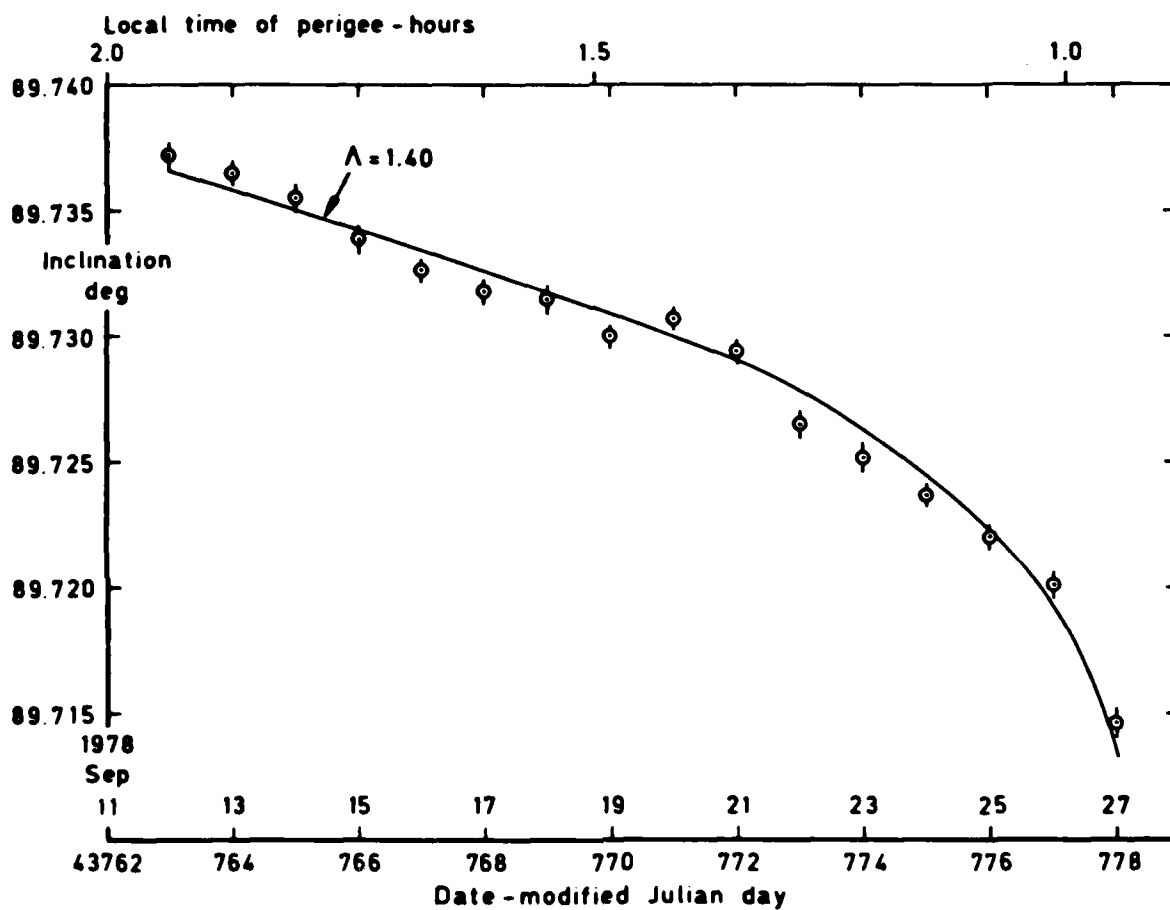Fig 8   Values of density scale height, with CIRA 1972 curves

Fig 9

Fig 9   Inclination values, cleared of perturbations, with fitted Λ-curve

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16. Descriptors (Keywords)   (Descriptors marked * are selected from TEST)
   Upper atmosphere winds. Upper atmosphere scale height. HEOS 2.
   Orbit determination.

17. Abstract   The polar orbit of Heos 2 second-stage rocket, 1972-05B, has been deter-
mined on each of the final 16 days before its decay in September 1978, using the RAE
orbit refinement program, PROP 6, with about 1360 observations. An accuracy of
30-70 m, both radial and across track, was achieved.

    Eleven values of density scale height have been determined from the decrease
in perigee height, with a 2 per cent error; seven of these values are within 6 per
cent of the CIRA 1972 reference-atmosphere values, the rms value being 4 per cent
higher than CIRA.

    The rotation rate of the upper atmosphere, Λ, was determined from the
decrease in orbital inclination as Λ = 1.40 ± 0.05 rev/day (to a strong
east zonal wind of 160 ± 20 m/s, at a mean height of about 240 km. The local time
was 01-02 h; solar activity was high; and the latitude of perigee moved steadily
from 10°N to 67°S.

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